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## **Required Statements**

"The contractor, The University of Sheffield, hereby declares that, to the best of its knowledge and belief, the technical data delivered herewith under Contract No F61775-00-WE063 is complete, accurate, and complies with all requirements of the contract.

**DATE:** 26<sup>th</sup> September 2002.

**Name and Title of Authorized Official:** Professor John H. Beynon"

- (A) "~~Disclosures of all subject inventions as defined in FAR 52.227-13 have been reported in accordance with this clause"~~
- (B) "I certify that there were no subject inventions to declare as defined in FAR 52.227-13, during the performance of this contract

**DATE:** 26<sup>th</sup> September 2002.

**Name and Title of Authorized Official:** Professor John H. Beynon"

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# **Investigating Strain Path Changes on Flow Stress and Microstructural Evolution in Ti-6Al-4V alloy during Hot Deformation**

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## **Summary**

Using the purpose built arbitrary strain path rig, hot deformation testing has been carried out on a commercial Ti-6Al-4V alloy. Initially, simple reverse torsion tests were performed, followed by tests combining torsion and uniaxial deformation. Optical and scanning electron microscopy have been used to assess the initial, heat treated and deformed structures. Bulk texture analysis has been carried out on the initial material, with EBSD used to assess micro-texture changes in heat-treated and deformed material.

## **Initial material**

The material was supplied as hot rolled, mill-annealed bar, diameter 30mm, having the composition shown in Table 1. The initial structure comprised equiaxed alpha, having a random texture.

## **Heat treatment**

To obtain a similar starting microstructure to that used by our collaborators, a four step heat treatment was carried out on each sample prior to testing. This comprised: 6 minutes at 815°C, 1 minute at 1040°C, 2 minutes at 950°C and finally 10 minutes at the test temperature, 815°C; for each temperature change a heating rate of 490°C/minute was used. Water quenching following heat treatment showed that this schedule resulted in a colony microstructure with a prior beta grain size of 110µm, a mean alpha lamella thickness of ~1µm and a 2µm thick grain boundary layer of alpha phase.

## **Hot deformation testing**

Isothermal tests were carried out on torsion samples having a gauge diameter of 6.60mm and length 13.20mm, see Figure 1. Two series of hot deformation tests were carried out, the first using forward and reverse torsion, in strain increments of 1 (Table 2). The second series used a torsion pre-strain of 0.33 followed by a combination of torsion/reverse torsion/compression to a total strain of 0.66 (Table 3). Monotonic torsion resulted in a peak flow stress followed by flow softening before steady state stress was reached at strains of ~0.5.

Series 1 – Strain reversal following forward torsion to a strain of 1 resulted in a reduction in the flow stress upon reloading, although difficulties with data recording meant that this could not be accurately quantified at the time. The 0° test was used to obtain a plot of the globularisation kinetics for forward torsion, as shown in Figure 2. This data was measured using point counting methods, from a series of back scattered electron (BSE) images taken at a magnification of x2000 across the diameter of an axial section. Measurements of the fraction globularised were also taken following a 180° strain path change and following a 180°+180° strain path change; these are also shown on Figure 2. In both cases, the globularisation is retarded compared with monotonic deformation. Bends/kinks were observed in the alpha lamellae following a single deformation, but many of these were straightened by a reverse deformation, as shown by the BSE images in Figure 3. Strain reversal also resulted in a coarser globularised grain size.

Series 2 – Figure 4 is an example of the flow curves obtained from the hot deformation tests, illustrating the flow response to a strain path reversal after a strain of 0.33 in torsion. Initially, flow softening is seen, followed by an increased work hardening rate until the steady state stress of the forward torsion test is achieved at the maximum strain. Due to the low torque values

associated with the strains/strain rates used in this work, the sensitivity was not sufficient to detect more subtle changes in flow behaviour for strain paths less than  $180^\circ$ . Axial sections were examined using BSE imaging techniques, and in all cases there was some kinking/bending of the alpha lamellae, but the low values of strain used in these tests meant no dynamic globularisation had occurred and any microstructural differences were subtle.

EBSM data from the heat-treated samples and both series of hot deformation samples requires further analysis to ascertain whether or not any significant conclusions can be drawn.

### Conclusions

- Strain path reversal resulted in flow softening greater than that seen during monotonic deformation, after both small (0.33) and large (1) pre-strains.
- The kinetics of dynamic globularisation are retarded by strain path reversal, which also results in an apparent straightening of previously bent alpha lamellae, and a coarsening of the globularised grains.
- Morphology changes due to strain path changes of less than  $180^\circ$  were not observed, probably due to the low strains used in this study.

### Figures & Tables

**Table 1 – Chemical composition (weight percent)**

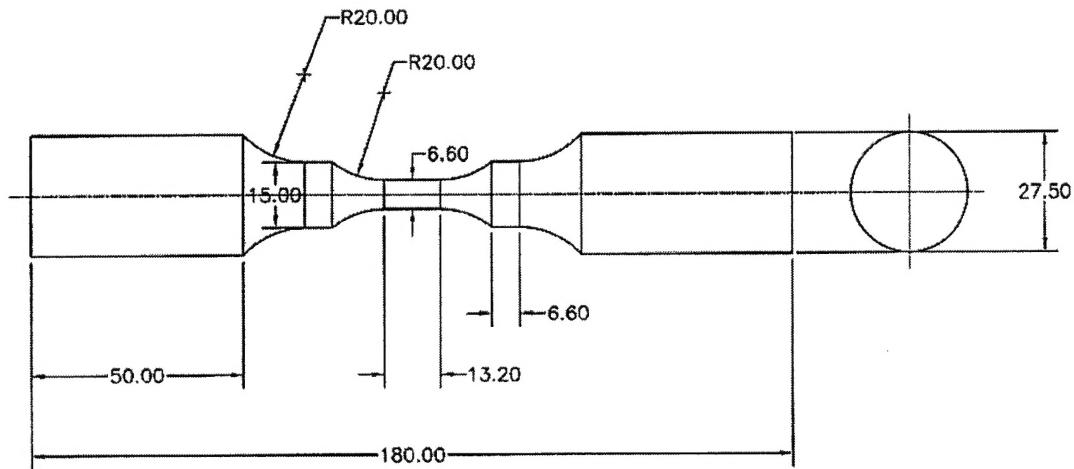
Al	V	Fe	C	N	O	Ti
6.6	4.1	0.14	0.06	0.007	0.2	Bal.

**Table 2 – Testing series 1**

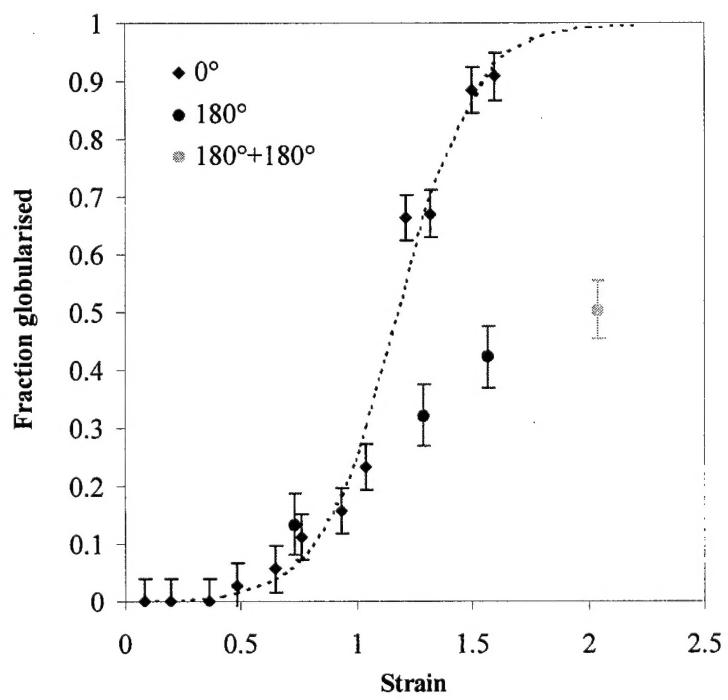
Strain 1	Strain 2	Strain 3	Strain path angle
Torsion 1	-	-	$0^\circ$
Torsion 1	Torsion 1	-	$0^\circ$
Torsion 1	Reverse torsion 1	-	$180^\circ$
Torsion 1	Reverse torsion 1	Torsion 1	$180^\circ + 180^\circ$

**Table 3 – Testing series 2**

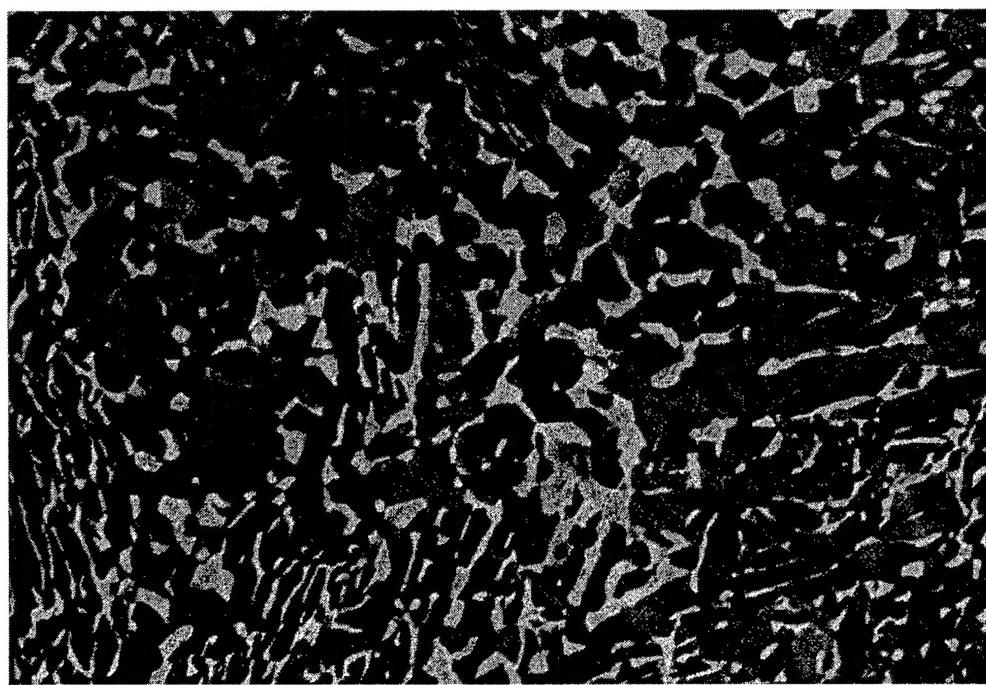
Pre-strain	Strain	Strain path angle
Torsion 0.33	Torsion 0.33	$0^\circ$
Torsion 0.33	Reverse torsion 0.33	$180^\circ$
Torsion 0.33	Compression 0.33	$90^\circ$
Torsion 0.33	Compression/reverse torsion 0.33	$135^\circ$



**Figure 1** – Diagram showing test piece dimensions in mm, general tolerance  $\pm 0.05\text{mm}$

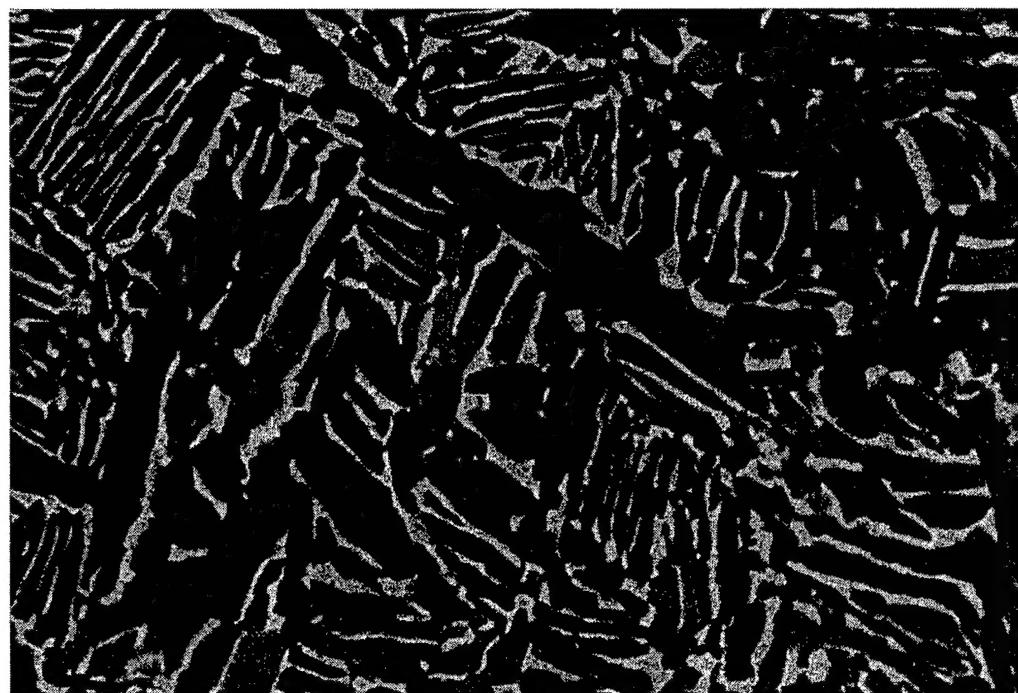


**Figure 2** – Globularisation kinetics from series 1, deformed in torsion/reverse torsion at  $815^\circ\text{C}$ , at a strain rate of  $0.001\text{s}^{-1}$



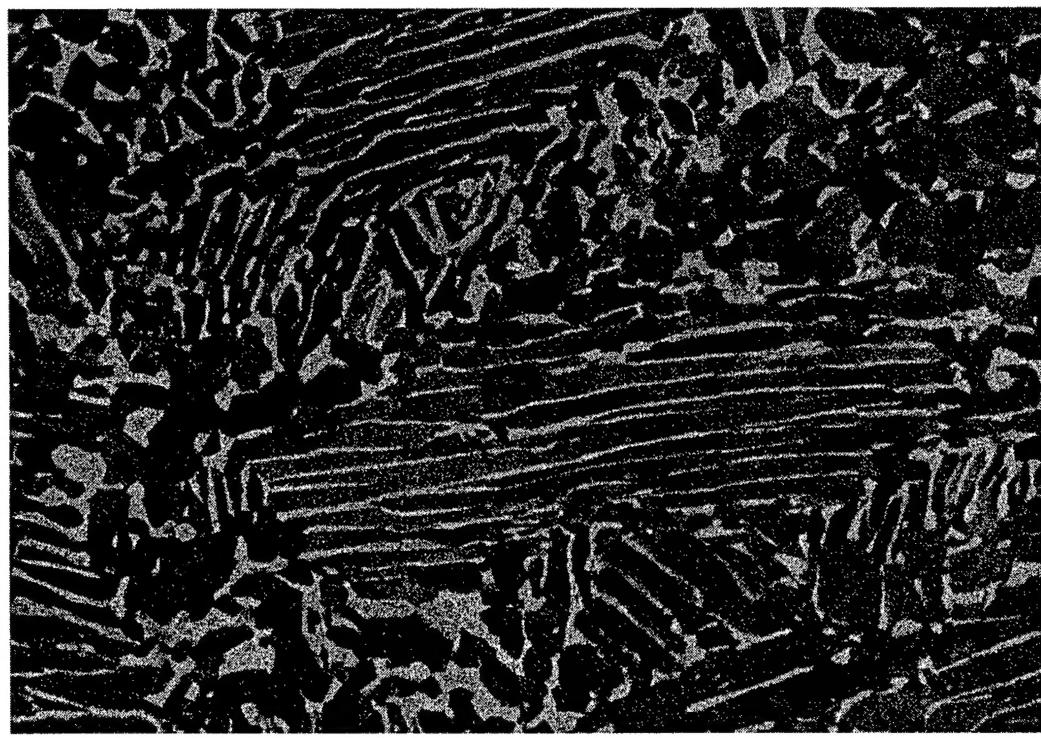
Monotonic torsion – local strain ~1.3, 66% globularised

10 $\mu$ m



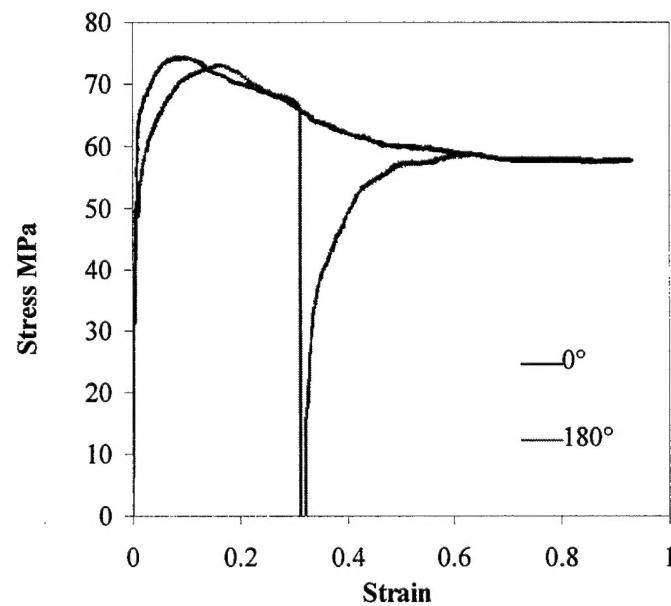
180° strain path change – local strain ~1.3, 32% globularised

10 $\mu$ m



180°+180° strain path change – local strain ~2.0, 50% globularised                    10µm

**Figure 3** – BSE images of deformed microstructures from series 1, deformed in torsion/reverse torsion at 815°C, at a strain rate of 0.001s<sup>-1</sup>



**Figure 4** – Flow curves from series 2, deformed in torsion/reverse torsion at 815°C, at a strain rate of 0.001s<sup>-1</sup>